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Name: Herbert M. Shapiro Signature Herbert M Shapiro

Case No.: IOS-118

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Sir:

Transmitted for filing is the Patent Application of

Inventor(s) : E. A. Mendoza et al.
Title : Thermally-Assisted Photolithographic Process Using Sol-Gel Derived Glass and Products Made Thereby
Assignee :
Priority(s) :
Assignee: Intelligent Optical Systems, Inc. Torrance CA 90505

CLAIMS AS FILED AND AMENDED

FOR	NO. FILED	NO EXTRA	RATE	FEE
Total Claims	32	12	9.00	108.00
Indep. Claims	7	4	39.00	156.00
Mult. Dep. Claims	0	0	-	-
		BASIC FEE	$345.00	
		TOTAL FILING FEE		$609.00

Enclosed are:

[ ] ____sheet(s) of formal drawings
[X] 8 sheet(s) of informal drawings
[X] 23 pages of specification with 32 claims and abstract
[X] in the English language
[ ] in a non-English language
[X] Declaration and Power of Attorney
[X] An Assignment
[ ] A certified copy of priority application(s)
[ ] A preliminary Amendment reducing the number of claims for filing purposes

[x] A check to cover the filing fee
[x] A $ **40.00** check for the assignment recording fee
[ ] A $ check for filing in a non-English language
[x] Declaration claiming Small Entity Status
[ ] The right of priority under 35 USC 119 is claimed on the basis of the aforementioned foreign application(s)
[x] Applicant/Assignee claims Small Entity Status

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Respectfully submitted,

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Enclosures: [x]

VERIFIED STATEMENT CLAIMING SMALL ENTITY STATUS (37 CFR 1.9(f) &1.27(c))—SMALL BUSINESS CONCERN

Applicant or Patentee: E. A Mendoza et al Docket No. IOS-118
Serial or Patent No.:
Filed or Issued: Concurrently
Title: Thermally-Assisted Photolithographic Process Using Sol-Gel Derived Glass And Products Made Thereby

I hereby declare that I am

☐ The owner of the small business concern identified below:

☒ An official of the small business concern empowered to act on behalf of the concern identified below:

NAME OF SMALL BUSINESS CONCERN: Intelligent Optical Systems, INc.
ADDRESS OF SMALL BUSINESS CONCERN: 2520 W. 237th Street, Torrance CA 90505-5217

I hereby declare that the above identified small business concern qualifies as a small business concern as defined in 13 CFR 121.12, and reproduced in 37 CFR 1.9(d), for purposes of paying reduced fees to the United States Patent and Trademark Office, in that the number of employees of the concern, including those of its affiliates, does not exceed 500 persons. For purposes of this statement, (1) the number of employees of the business concern is the average over the previous fiscal year of the concern of the persons employed on a full-time, part-time or temporary basis during each of the pay periods of the fiscal year, and (2) concerns are affiliates of each other when either, directly or indirectly, one concern controls or has the power to control the other, or a third party of parties controls or has the power to control both.

I hereby declare that rights under contract or law have been conveyed to and remain with the small business concern identified above with regard to the invention described in:

☒ the specification filed herewith with title as listed above.

☐ the application identified above

☐ the patent identified above

If the rights held by the above identified small business concern are not exclusive, each individual, concern or organization having rights in the invention must file separate verified statements averring to their status as small entities, and no rights to the invention are held by any person, other than the inventor, who could not qualify as an independent inventor under 37 CFR 1.9(c) if that person made the invention, or by any concern which would not qualify as a small business concern under 37 CFR 1.9(d), or a nonprofit organization under 37 CFR 1.9(e).

Each person, concern or organization having any rights in the invention is listed below:

☒ no such person, concern, or organization exists.

☐ each such person, concern or organization is listed below.

Separate verified statements are required from each named person, concern or organization having rights to the invention averring to their status as small entities. (37 CFR 1.27).

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b))

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

NAME OF PERSON SIGNING Reuban Sandler

TITLE OF PERSON IF OTHER THAN OWNER President & CEO

ADDRESS OF PERSON SIGNING 2520 W. 237th Street, Torrance ~~CA 90505-5217~~

SIGNATURE Reuban Sandler DATE 5/19/00

THERMALLY-ASSISTED PHOTO-LITHOGRAPHIC PROCESS USING SOL-GEL DERIVED GLASS AND PRODUCTS MADE THEREBY

REFERENCE TO RELATED APPLICATIONS

This application is related to a companion application, Serial No. __________, (IOS-118A), filed on even date herewith and assigned to the assignee of the present application.

FIELD OF THE INVENTION

This invention relates to sol-gel derived glass thin films and, more particularly, to a thermally-assisted process for fabricating both passive and active devices therein as well as to the devices so fabricated.

BACKGROUND OF THE INVENTION

The sol-gel process for forming glass is well known in the art. Further, it is well known to fabricate passive devices such as waveguides, splitters and directional couplers, and grating structures as well as thermo-optic switches using photolithographic processes. Canadian Demand Application No. 2,218,273 describes a solvent-assisted lithographic process in use by Lumenon Innovative Lightwave Technologies, Inc. and is incorporated herein by reference.

The above-identified patent describes a process including the sequence of steps for forming a silicon dioxide layer on a silicon substrate, depositing a photosensitive sol-gel layer on the silicon dioxide layer, exposing the sol-gel layer to a pattern of ultra violet light to solidify portions of the sol-gel layer, and (wet) etching to remove the non-solidified portions of the sol-gel layer. The solidified portion of the sol-gel layer, in one embodiment, comprises an elongated ridge for defining a waveguide. A cladding layer is added on top of the ridge resulting in a non-planar surface.

A doctoral thesis entitled: "Photolithography of Integrated Optic Devices in Porous Glasses", City University of New York, 1992 by E. Mendoza, one of the applicants herein, describes techniques for fabricating integrated optic devices in porous glass employing a variety of reactants. The thesis describes sol-gel as a technique for forming bulk porous glass.

BRIEF DESCRIPTION OF THE INVENTION

The present invention is directed at extensions of the bulk techniques described in the above-noted theses to sol-gel thin films. Specifically, a technique for the photolithographic fabrication of integrated optic structures in thin films of photosensitive sol-gel glasses is described here. This technique involves the formation of a photosensitive sol-gel, including an organometallic photosensitizer, on a suitable substrate (glass, silicon, or any other support material). Next, the photosensitive film is exposed to white or ultraviolet light inducing a photochemical reaction in the photosensitive sol-gel glass network with the end photo-product being a metal oxide. The photodeposited metal oxide is permanently bound to the sol-gel film glass network as a glass modifier during a heat treatment process, which in turn induces a permanent refractive index increase in the glass. The refractive index increase is dependent on the concentration of the photosensitizer and on the light energy used in the exposure process. Therefore, a spatially varying light intensity during exposure results in a spatially varying refractive index profile. This refractive index profile induced in the film can be designed to guide light.

Exposure of the photosensitive sol-gel film to white or ultraviolet light induces the unbinding of the metal from the photolabile moiety component of the photosensitizer

followed by the binding of the metal to the sol-gel film. The exposed regions of the sol-gel film are converted to a metal oxide silica film by first and second step heatings at a low temperature and high temperature, respectively. The low temperature drives out the unexposed (unbound) photosensitizer and the unbound photolabile moiety. The higher temperature step unbinds the organic component from the bound photosensitizer and drives it off. This step also permanently binds the metal to the silica film forming a metal oxide glass modifier. If the sol-gel film is deposited in a glass or silicon substrate, a metal oxide doped silica region of Si-O-M-O-Si is formed in the exposed regions acting as a glass modifier which in turn modifies the refractive index. The unexposed photosensitizer is driven off during the heat treatment steps. Since no material is removed from the sol-gel film in this process, as in the case of prior-art-processes, the resulting top surface is planar, thus leading to a simpler process for producing devices and increase lifetime of resulting devices.

The index of refraction of the light guiding waveguide is determined by the concentration of the metal oxide and by the type of metal oxide (GeO_2, SnO_2, PbO_2, TiO_2, among others) photodeposited. Accordingly, a buried waveguide of metal oxide doped silica material of relatively high index of refraction is sandwiched between regions of a dielectric material with relatively lower index of refraction. Therefore, the change in refractive index between the metal oxide doped silica waveguide and the dielectric material is controlled by the concentration of the metal oxide and by the type of metal oxide. If the photodeposited metal oxide doped waveguide exhibits non-linear optical properties (semi-conductive, electro-optic, magneto-optic, and/or all-optical) active optical devices can be realized in this material system. If electrodes are attached

adjacent to the waveguide and a voltage applied, for example, an electro-optic switch or an optical modulator may be formed using a varying electrical field for varying the index of refraction of the waveguide. The temporary change in refractive index can be used to switch or modulate the light guided through the waveguide.

The invention thus is based on the realization that the richness in the number and variety of constituents which can be included in a sol-gel film enable unique integrated optic structures to be fabricated, particularly with the use of photo masks, which are not achievable with alternative techniques. Specifically, the technique permits a high degree of control not only in defining high index of refraction channels in a sol-gel film but also in controlling the index of refraction incrementally along the length of the channel and from channel to channel in multichannel devices such as wavelength division multiplexers (WDM). Accordingly, the index can be changed to enable strongly guided waveguides to be fabricated creating low-loss, small bend radii thus permitting a large number of channels to be fabricated in a single film. A two-hundred and fifty-six channel wavelength division multiplexer , for example, can be made in a very small chip because of the tailoring of the indices of refraction channel to channel and along the length of the channel. Moreover, the ends of the channels can be made with indicies of refraction to obtain NA matching to optical fibers.

Further, because the technique produces buried channels (waveguides) and since the buried channels can be made in successive sol-gel glass films, multiple layer devices can be realized, each layer (film) having a plurality of channels.

The high degree of control of the index of refraction along a channel length also permits Bragg gratings to be formed simultaneously with the formation of a channel, thus

providing a simple technique for producing, for example, integrated optic lasers. Abundance of compatible constituents such as erbium, for example, also permits amplification of light signals in the channels. Other constituents allow for the formation of electro-optically active waveguides permitting, for example, modulation of light signals in the waveguide.

The technique not only permits the foregoing unique structures to be fabricated but also permits the fabrication of optical couplers, splitters, switches, tunable filters, amplifiers, modulators, combiners, directional couplers, optical add-drops, gratings, both active and passive devices described, for example, in *Optical Fiber Communications 111B*, Academic Press, New York edited by Ivan P. Kaminow and Thomas L. Koch, 1997.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig's 1 and 2 are schematic side views of alternative generic structures in accordance with the principles of this invention;

Fig's 3, 4 and 5 are schematic side views of electro-optic, magnetic-optic and optical switches, respectively, in accordance with the principles of this invention;

Fig's 6 and 7 are schematic side views of a tunable Bragg grating and a tunable add/drop filter in accordance with the principles of this invention.

Fig. 8 is a block diagram of the method for fabricating the structure of fig's 1 and 2;

Fig's 9, 10, 11 and 12 are schematic top views of alternative waveguide structures in accordance with the principles of this invention;

Fig's 13 and 14 are schematic projection and top views of a variable index waveguide array used in a wavelength division multiplexer and a gray scale mask for the fabrication thereof, respectively;

Fig. 15 is a graph of waveguide propagation loss versus channel bend;

Fig. 16 is a schematic illustration of an array of curved waveguides with variable refractive indices for use in the fabrication of array waveguide grating structures for WDM applications;

Fig. 17 is a schematic representation of a prior art "Chirped" Bragg grating;

Fig. 18 is a schematic representation of a "Chirped" Bragg grating structure in accordance with the principles of this invention;

Fig. 19 is a schematic representation of a multilayer device each layer of which includes an array of curved waveguides such as those shown in fig. 16; and

Fig. 20 is a block diagram of the method for fabricating the multilayered structure of fig. 19.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS OF THIS INVENTION

The invention is based on the recognition that a photosensitive sol-gel film including an organometallic photosensitizer can be made into a metal oxide material when exposed to ultra violet or white light in the wavelength range of from about 200 nm to 700 nm followed by a controlled heat treatment. The invention is further based on the realization that the exposure of such a film to that light through a photo mask can be made to produce a waveguide channel of relatively high index of refraction, metal oxide material sandwiched between regions of dielectric, low refractive index material. Furthermore, based on the selection of appropriate precursors, the photodeposited metal

oxide doped waveguide exhibits non-linear optic properties (semiconductive, electro-optic, magneto-optic and/or all optic) so that electrodes placed adjacent to the waveguide for creating electric fileds in response to applied voltages can induce temporary charges in the refractive index of a waveguide. .

In this context, fig's 1 and 2 show schematic side views of a work piece 10 and 20 respectively. In fig. 1, a silicon substrate 11, 6" x 6" x 1 mm is coated with a silicon dioxide (deposited or grown) layer 1 - 2 microns thick. The silicon dioxide layer has a photosensitive sol-gel film 13 formed on it by well understood techniques such as spinning and/or dip coating.

In fig. 2, the substrate 21 comprises glass, in which case no silicon dioxide layer is required. A photosensitive sol-gel film 23 is formed directly on the glass substrate.

The sol-gel film is represented, in fig's 1 and 2, as having R-M-X chemical constituents in it. These materials are added to the sol-gel by dissolving them in the sol-gel solution. The sol-gel film illustratively has a thickness of about 1 – 5 microns.

The notation – R – refers to anyone of a group of volatile organic materials including CH_3; $CH_3 - CH_2$; $CH_3 - CH_2 - CH_2$ - and the like. The notation – M – refers to any one of the metals of group IVA of the periodic table including Ge, Sn and Pb; group VI including Se and Te; group VIII including Fe, Co, Ni; and group IVB including Ti and Zn and rare earth metals such as En, Eu, Pr and Tu. The concentration of the metal determines the index of refraction of the sol-gel film in conjunction with the engery of the light used in the subsequent exposure steps.

The – X – notation is the photolabile component of R – M – X and represents a halogen which includes chlorine, bromine, iodine and fluorine, but also carbonyls (CO).

The photosensitive sol-gel film, in accordance with the principles of this invention initially includes R – M – X as indicated in each of fig. 1.

The photosensitive sol-gel film (13 or 23) is exposed to white or ultra violet radiation through a mask to define, illustratively, three regions. The regions are identified in fig. 1 as exposed region 31 with unexposed regions 32 and 33 defining interfaces 34 and 35 with region 31 respectively. Fig. 1 also can be seen to include a silicon substrate and a silicon dioxide surface layer.

Fig. 3 is a top view of an electro-optic switch 40 including first and second waveguiding channels 41 and 42 fabricated as described in connection with fig's. 1 and 2. The channels are in close proximity to one another at region 43. Electrodes 44 and 45 are formed over channel 41 and channel 42, respectively, at region 43. A voltage, indicated by the V+ and V- signs, produces a localized change in the index of refraction that causes a signal, P_{in}, in channel 41 to exit channel 42 (P_{o2}). In the absence of such a voltage, the signal (P_{in}) exits channel 41 (P_{o1}). Thus, a high-speed electro-optic switch is realized.

Alternatively, electrodes 44 and 45 may be formed directly in the sol-gel film by using a photosensitizer that leads to the deposition of a high conductivity material when exposed to light. To this end, a photosensitized thin film is exposed through a mask to form the electrodes and then heat treated to remove the photosensitizer but at a temperature which avoids consolidating the film. Next a second photosensitizer is introduced into the film, exposed through a mask to form the waveguide and the heat treatment to remove the photosensitizer and consolidate the film is carried out.

Fig. 4 shows a magneto-optic switch fabricated as discussed in connection with fig's 1 and 2 using an M constituent which confers magnetic properties to channels 50

and 51 in fig. 4. Magnets 52 and 53 are positioned at region 54 at which the channels come into close proximity. In the presence of a magnetic field, an input signal Pin in channel 50 exits channel 51 (Po2). In the absence of a magnetic field, the signal exits channel 50 (Po1).

Fig. 5 shows an all optical switch 60 with channels 61 and 62. The channels are in close proximity at region 63. Region 63 includes an optically active dopant. If pump light is introduced at the input 65 of channel 62, a signal Pin at the input of channel 61 exits channel 62 (Po2). In the absence of pump light, the signal exits channel 61 (Po1).

Fig's 3, 4, 5, 6 and 7 are illustrative of electronic, magnetic or optic field control which permit entire categories of devices to be fabricated. These include modulators, directional couplers, tunable gratings and total internal reflection deflectors among others.

The inclusion of materials such as tin oxide, lead oxide, titanium oxide, and Zirconium oxide, thulium oxide allows for the fabrication of electro-optic switches. The inclusion of materials such as iron, iron oxide, nickel and nickel oxide allows the fabrication of magneto-optic switches. The inclusion of rare earth materials such as erbium oxide, neodymium oxide, ytterbium oxide and praesodymium oxide allows the fabrication of all optical switches.

The operating principle of the electro-optic switch is based on the use of a metal oxide waveguide with electro-optic properties. The variation of an electric field to many electro-optic materials leads directly to a variation in the real and imaginary components of the refractive index. This effect can be used for switching in an integrated optic device, based on a waveguide proximity coupler structure as shown in fig. 3. In this

design, when the voltage is off the light beam Pin travels directly through the waveguide with output P_{o1}, when the field is on, the induced refractive index change causes the light beam to couple into the adjacent waveguide with output P_{o2}. Turning the voltage off causes the light to return to its original state with output P_{o1}.

Similar effect occurs in the case of the magneto-optic switch. In this case a waveguide with magneto-optic properties is used, such that the variation of a magnetic field in the vicinity of the magnetic waveguide leads directly to a variation in the real and imaginary components of the refractive index. Hence, by applying a magnetic field to the structure, the light output in fig. 4 can be switched between the two waveguide arms (P_{o1} and P_{o2}) of the structure.

Similarly, the operating principle of the all-optical switch is based on the use of a dopant material on the active part of the integrated optic structure, the refractive index of which (real and imaginary components) is modified when excited by an external laser source (light pump) as shown in fig. 5. In this design, when the light pump is off the light beam Pin travels directly through the waveguide with output P_{o1}. When the light pump is turned on, the induced refractive index change causes the light beam to couple into the adjacent waveguide with output P_{o2}. With the pump off, the light returns to its original state with output P_{o1}.

Fig. 6 illustrates a tunable Bragg grating filter operable to reflect a selected wavelength. The figure shows a channel 70 fabricated as discussed in connection with fig's 1 and 2. The Bragg grating is indicated at 71 and electrodes 72 and 73 are located to produce an electric field to change the index of refraction of the channel at the grating. In

the presence of the field, an input signal with wavelengths λ1, λ2 --- λx --- λn exits the channel with wavelength λx reflected as indicated.

Fig. 7 illustrates a tunable add/drop filter fabricated as described in connection with fig's 1 and 2. The filter includes channels 80 and 81 with a common section 82 which includes a Bragg grating 83. Electrodes 84 and 85 are positioned to generate an electric field which changes the index of refraction in section 82. An electrical field applied to the electrodes tunes the Bragg wavelength to the value λy depending on the magnitude of the electrical field to that wavelength λx exits channel 81 at 87 and may be added at 88.

The devices of fig's 3 through 7 are produced by exposing a photosensitive sol-gel film to visible or ultra violet light. The light is operative to unbind the photosensitizer (X) component and to bind the metal (M) permanently in the exposed region. The light, illustratively, is ultra violet in a wavelength range of about 200 nm – 400 nm and visible in the wavelength range of 400 nm to 700 nm and exposure is for 5 minutes to 48 hours duration depending on light intensity.

The light exposure is followed by a sequence of first and second heating steps. The first heating step is at a temperature of about 300° C for a period of 1 hour and results in the driving off of the sensitizer from the entire sol-gel layer. The second heating step is at about 900°C for about 1 hour duration and results in the unbinding of the R component and the driving off of that component from the entire sol-gel film. A subsequent heating step at about 1050° C can consolidate the pores in the sol-gel film yielding a solid, non-porous glass. The resulting structure, as shown for example in fig. 3, includes channels 41 and 42 comprising Si – O – M – O – Si materials and regions

outside the channels comprising SiO_2. The channels are a metal oxide doped silica region in the embodiment of fig. 4; the regions outside the channels are electrically insulating.

The metal oxide induced by the binding of the component (M) in region 31 (of fig. 1) defines the index of refraction in the channels. Accordingly, the concentration of metal oxide can be selected so that the index of refraction in the channels relates to the indicies of refraction in regions outside the channels to define a waveguide for light. A voltage signal impressed between electrodes as indicated in fig. 3, permits further control of the index of refraction in the channels and thus to the deflection of the signals passed through the waveguide.

Fig. 8 is a flow diagram of the method for fabricating the device of fig. 3. Specifically, block 91 indicates the formation of a photosensitive sol-gel film on a suitable substrate such as silica glass or silicon containing a thermally grown silica layer. Block 92 indicates the exposure of at least one channel of the sol-gel layer to (visible or) ultra violet light. Block 93 represents the first heating step of about 300°C to evaporate the unexposed photosensitizer (X). Block 94 represents a second heating step at about 900°C to evaporate the organic material (R) from the layer.

The photosensitive sol-gel process permits the precise control of refractive index to produce a variable refractive index distribution along the horizontal plane of the film. To obtain variable refractive index gradient waveguide channels, the photosensitive sol-gel film (13 of fig. 1) is exposed using a photo mask. Exposure to UV-visible light through the mask induces a photochemical reaction of the photosensitizer immobilized in the sol-gel matrix. A percentage of photosensitizer transforms to a metal oxide

depending on the degree of light exposure (controlled by the photo mask). The metal oxide acts as a refractive index modifier of the silica film. Thus, the use of a gray-scale photo mask allows the concentration of metal oxide, or refractive index profile, along the light propagation path of the waveguide (channel) to be controlled.

The ability to precisely control the refractive index of the waveguide during the light exposure process allows the fabrication of structures with complex index profiles. These include the ability to fabricate waveguides such as the one shown in fig. 9 with altered index profiles. In this waveguide design it is possible to combine regions of small refractive index change forming weakly guiding waveguides with numerical apertures matched to that of telecommunication fibers, with regions of high refractive change forming strongly guiding waveguides, and back to regions of small refractive index change forming weakly guiding waveguides. This variation in index can be graded adiabatically to eliminate the reflections associated with abrupt changes in index of refraction. The combination of these waveguide structures allows the coupling of fibers to the waveguide as well as to have the creation of regions with special properties, i.e. passive waveguides with variable refractive indexes such as gratings (fig. 10), or tight bends such as those used in phase array grating designs (fig. 11), or active waveguides with regions that exhibit electro-optic or magneto-optic activity (fig. 12).

Fig. 13 is a schematic representation of an integrated optic chip waveguide array illustratively including four channels 120, 121, 122, and 123. The difference between the refractive index of the core (n_z) and the refractive index of the cladding (n_1) is expressed as Δn. Thus, the Δn for channel 120 is $n_n - n_1$ the Δn for channel

121 is $n_4 - n_1$, the Δn for channel 122 is $n_3 - n_1$, and the Δn for channel 123 is $n_2 - n_1$.

The fabrication of the structure of fig. 13 is as described hereinbefore except that a photo mask is used as shown in fig. 14. As can be seen in the figure, the mask for channel 123 is almost black; the mask for channel 122 is dark gray, the mask for channel 121 is a lighter gray and even lighter for channel 120. Additional channels would require lighter and lighter masks as indicated in the figure, the range going from totally black to clear. The regions between the channels (the cladding) require a clear portion of the mask. The use of the photo mask allows all the channels to be defined simultaneously.

The effect of variable refractive index is based on the photo-chemistry of the photosensitive sol-gel film where for each photon of light a photosensitive molecule is transformed into a metal-oxide. Each of the metal oxide particles induces a refractive index change in the glass. The larger the number of metal oxide particles photo-produced, the larger the refractive index change. Consequently, by using a photo mask, we can produce a variable index integrated optic chip because the darker regions of the mask allow fewer photons to expose the chip than the lighter regions of the mask.

This same procedure can be used in the fabrication of an array of curved waveguides with variable refractive indices. By controlling the refractive index of the curved waveguides (channels) during the light exposure process, we can produce curved waveguides with smaller and smaller bending radii. Since the bending radius is directly related to the refractive index change of the waveguide, the larger Δn (fig. 13), the smaller the bending radius.

Fig. 15 is a graph of waveguide propagation loss (db) versus bend. It is clear from the figure that the losses for the small bend (Δn_n) is the same for the losses for the large bend (Δn_1). This property allows for the fabrication of dense (highly packed) curved waveguide arrays because very small bending radii can be achieved. Fig. 16 shows schematically an array of curved waveguides 150, 151, 152, 153, 154, and 155 with variable indices with radii of curvature becoming increasingly smaller from channel 150 to channel 155.

The simultaneous control of refractive index differential is particularly useful in the fabrication of dense and ultra-dense, variable-index, phase – array – waveguide gratings commonly used for fabricating integrated optic WDMs; the WDM structure typically requires curved waveguides in the array. Thus, the use of a gray – scale mask and the resulting ability to achieve a variable and/or controlled refractive index in such an array allows the fabrication of highly – packed chips in a relatively small package.

This property also is useful for producing chirped Bragg gratings useful for dispersion compensation in telecommunication systems. Fig. 17 illustrates such a prior art device. Fig. 17 shows a channel 160 with stripes 161, 162, 163 - - - n where the refractive index difference Δn is constant and the spacing between stripes is different.

In accordance with the principles of this invention, a chirped Bragg grating structure, is characterized by a refractive index change and the spacing between stripes is constant. Fig. 18 shows a chirped Bragg grating structure formed in a photosensitive sol-gel film with stripes 170, 171, 172 - - - N where the spacings 174, 175, - - - are constant but the change in index of refraction $\Delta\eta$ varies from $\Delta\eta_1$ to $\Delta\eta_2$ and . . . $\Delta\eta_n$ along the length of the grating. The use of a photo mask permits easy control over the index of

refraction difference particularly in grating structures where the periodicity is typically sub-micron.

Fig. 19 shows film 149 of fig. 16 formed on a substrate 181 which may comprise glass or silicon with an S_iO_2 surface layer as discussed hereinbefore. The sequence of heating steps causes a shrinkage in the thickness (vertical dimension) of film 149. But the film otherwise provides a suitable planar substrate for the formation of additional films in each one of which may be formed a multichannel device (as for example) shown for film 149.

Fig. 19 shows one such additional film 182 extending between an input 183 of multimode light (typically via an optical fiber not shown) and an output indicated by arrows 184.

A multilayered device of the type shown in fig. 19 is fabricated by the method described in connection with the flow diagram of fig. 20. The flow diagram indicates the steps 91 – 94 of fig. 8 are carried out to produce film 149 of fig. 19 as indicated by block 190. Thereafter, the film produced by steps 91 – 94 is used as a substrate for a second film (181) as indicated by block 195 of fig. 20. The sequence of steps is repeated for each film required as indicated by block 196.

A multilayered device as shown in fig. 19 is relatively easy to fabricate because of the variety of materials available, the use of a gray scale mask, and the fact that buried (waveguides) channels are produced and the fact that films having thickness (greater than one micron) suitable for integrated optics devices do not shrink laterally.

WHAT IS CLAIMED IS:

1. Apparatus comprising a first thin photosentitive sol-gel film (including an organometallic photosentizer) on a substrate containing oxygen and silicon, said sol-gel film including at least first and second spaced apart regions which include $Si\,O_2$ with a high index of refraction channel therebetween, said channel including $Si - O - M - O - Si$ where M is a metal, said channel including different indices of refraction along the axis thereof.

2. Apparatus as in claim 1 wherein said substrate comprises glass.

3. Apparatus as in claim 1 wherein said substrate comprises silicon, said substrate including a surface layer of silicon dioxide.

4. Apparatus as in claim 1 wherein said first channel includes $Si - O - M - O - Si$ said channel having a relatively high index of refraction compared to that of adjacent regions of said film, said channel including at least a portion comprising alternating regions of $Si - O - M - O - Si$ and $Si\,O_2$ for defining a grating.

5. Apparatus as in claim 4 wherein said regions of SiO_2 have different dimensions along the axis of said channel.

6. Apparatus comprising a substrate having a silica surface layer, said apparatus including a thin sol-gel glass film thereon, said thin sol-gel film including therein at least a first metal oxide waveguide channel having a relatively high refractive index.

7. Apparatus as in claim 6 also including first and second electrodes formed astride said metal oxide with electro-optic properties channel and responsive to a voltage impressed thereon to vary the index of refraction locally therein.

8. Apparatus as in claim 7 including a plurality of metal oxide waveguide channels each comprising $Si - O - M - O - Si$ where M is a metal taken from a class consisting of groups IVA and IVB, Group VI, transition metals and rare earth metals from the periodic table the index of refraction in said channels varying differently in each.

9. Apparatus as in claim 6 wherein said substrate comprises a glass.

10. Apparatus as in claim 6 wherein said substrate comprises silicon having a surface layer of silicon dioxide.

11. Apparatus comprising a substrate having a silica surface layer, said apparatus including a thin sol-gel glass film thereon, said sol-gel film including therein at least first and second metal oxide (waveguide) channels, said channels being in close proximity only in a first region thereof, said apparatus including signal-responsive means for switching light signals from said first to said second channel controllably.

12. A method for forming a high refractive index metal oxide waveguide channel in a sol-gel derived glass, said method comprising the steps of forming a photosensitive sol-gel film including an organometallic photosensitizer on a silica substrate said method comprising the steps of exposing said film through a mask to light of a wavelength and for a time for unbinding different amounts of metal constituents and of said sensitizer in different sections along at least a first channel thereof, exposing said film to heat at a first temperature and for a time to drive off the unbound sensitizer and to bind the metal constituents of said sol-gel film, and exposing said layer to heat at a second temperature higher than said first temperature for a time to unbind and drive off the organic constituents of said sol-gel film.

13. A method as in claim 12 wherein the step of exposing said layer to ultraviolet light is carried out through a photo mask for confining said light to a first channel of said film, and for defining second and third unexposed regions to first and second sides of said channel, said unexposed regions defining first and second interfaces with said first channel respectively.

14. A method as in claim 13 wherein said step of exposing said layer to ultra violet light through a photo mask defines a plurality of spaced – apart first channels, each of said first regions having first and second interfaces with second and third unexposed regions respectively, said channels having differently varying indicies of refraction therealong.

15. Apparatus comprising a substrate having a silicon dioxide surface, said apparatus including a photosensitive sol-gel derived glass film thereon, said film including at least a first channel therein having an index of refraction sufficiently higher therein than the index of refraction in adjacent regions to confine therein light introduced at an input thereof, said channel having a continuous variation in index of refraction therealong.

16. Apparatus as in claim 15 including a first plurality of said channels organized along closely spaced paths between said input and an output, each of said channels having a continuously-varying index of refraction different from that of any other one of said channels..

17. Apparatus as in claim 16 wherein each of said channels is configured to transmit light of a different wavelength.

18. Apparatus as in claim 1 wherein the index of refraction in said channel changes in a manner to define spaced apart Bragg gratings for reflecting light therebetween.

19. Apparatus as in claim 18 in which said channel comprises Si – O – M – O - Si and said adjacent regions comprise SIO where Si is silicon, O is oxygen and M is a metal.

20. Apparatus as in claim 1 also including first and second electrodes connected to said channel at first and second interfaces with said adjacent regions to first and second sides thereof.

21. Apparatus as in claim 16 comprising a plurality of photosensitive sol-gel derived glass films, said apparatus including n pluralities of said channels arranged in each of said film each of said n pluralities extending between an input and an output.

22. Apparatus as in claim 20 also including means for impressing a voltage between said first and second electrodes.

23. Apparatus as in claim 1 wherein a portion of said channel comprises magnetic material, said apparatus also including means for generating a magnetic field in at least said portion of said channel.

24. Apparatus as in claim 22 wherein said electrodes are connected to a first portion of said channel and said channel divides into first and second derivative channels at said portion.

25. Apparatus as in claim 23 wherein said means for generating is coupled to a first portion of said channel and said channel divides into first and second derivative channels at said portion.

26. Apparatus as in claim 1 having a plurality of high index of refraction channels therein extending from a common input to a common output, each of said channels having a different radius of curvature for providing a low loss transmission path for a different wavelength therein.

27. Apparatus as in claim 26 also including fiber optic means for introducing at said input light having a band of wavelengths including each of said different wavelengths.

28. Apparatus as in claim 27 wherein said film includes means for dividing said band of wavelengths into a set of individual wavelengths, one for each of said channels.

29. Apparatus as in claim 27 including at least a second sol-gel film on said first sol-gel film, said second sol-gel film also including a plurality of high index of refraction channels therein extending from a common input to a common output, each of said channels in said second film having a different radius of curvature for providing a low loss transmission path for a different wavelength therein.

30. Apparatus as in claim 28 having first and second optical fibers coupled to the common inputs of said first and second film respectively for introducing input light having a band of wavelengths including each of said different wavelengths.

31. A method for forming a multilayered sol-gel film device, said method comprising the steps of 1) forming a first sol-gel film including components $R - M - X$ on a substrate containing SiO_2, 2) exposing the film to light through a mask for unbinding X and binding M, 3) heating the film at a first temperature and for a time to drive off X and permanently bind M to SiO_2, 4) heating the film at a second higher temperature to drive off R and M from unexposed regions of the film, 5) forming a second sol-gel film and said first sol-gel film and repeating steps 2), 3), and 4).

32. A method for forming an integrated optic chip including a plurality of high index of refraction channels having a longitudinal axis extending from an input to an output end, said method comprising the steps of forming an photosensitive sol-gel film including an organomatillic photosensitizer on the surface of a substrate having a surface composed of silicon dioxide, exposing said sol-gel film through a gray scale mask to radiation of a wavelength and for a time to bind differing amounts of metal constituents of said sol-gel film to said silicon oxide and to unbind said photosensitizer, said mask having different regions of opacity for each of said channels for producing in said channels differing concentrations of said metal constituents therein, heating said sol-gel film at a first temperature and for a time to drive off said sensitizer and bind said different amounts of said metal constituents to the silicon dioxide in said channels permanently, and heating said sol-gel film at a second relatively higher temperature for unbinding the organic constituents of said sol-gel film and for driving off the organic constituents.

ABSTRACT OF THE DISCLOSURE

A photosensitive sol-gel film containing an organometallic photosensitizer is deposited on the oxide containing surface layer of a silicon substrate. A pattern of white or ultra violet light incident to the photosensitive sol-gel film results in the unbinding of the photosensitizer from the exposed regions of the sol-gel film. A subsequent succession of first and second heating steps results in, first, the removal of the photosensitizer constituents from the exposed regions of the sol-gel film and, second, the removal of the organic constituents from the exposed regions, resulting in regions doped with a metal oxide with non linear optical properties (semicondutive, electro-optic, magneto-optic, etc.) properties. The location of electrodes on the interfaces of the exposed metal oxide waveguide regions with the unexposed regions results in an electric field modifying the index of refraction locally in response to an impressed voltage therebetween. Optical switches, couplers, waveguides, splitters, interferometers wavelength division multiplexer, Bragg gratings and more can be fabricated. A glass substrate also may be employed, instead of a silicon, in which case a separate silicon oxide surface layer is unnecessary. In the case where the exposed region includes magnetic material, a magneto-optic switch can be fabricated by the process.

Fig 1

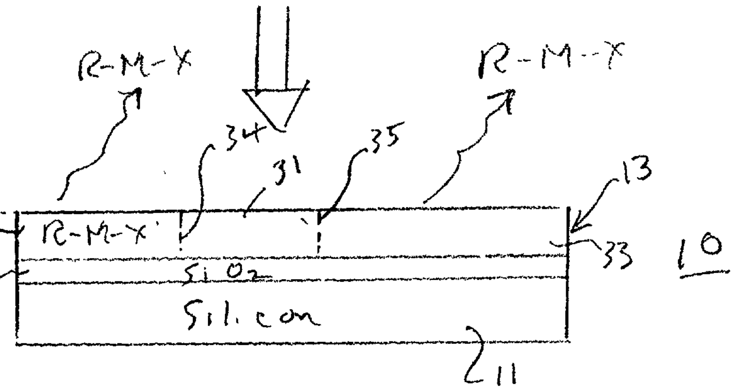
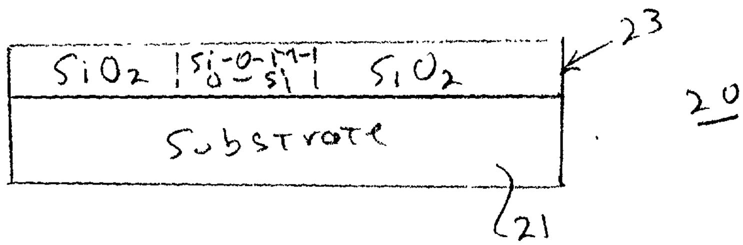


Fig 2



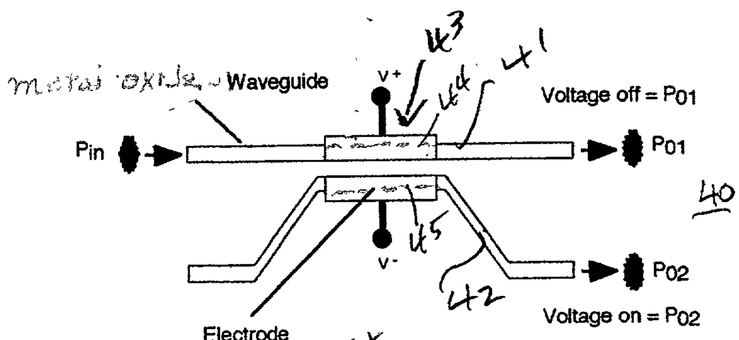


Fig 3
Electro-Optic

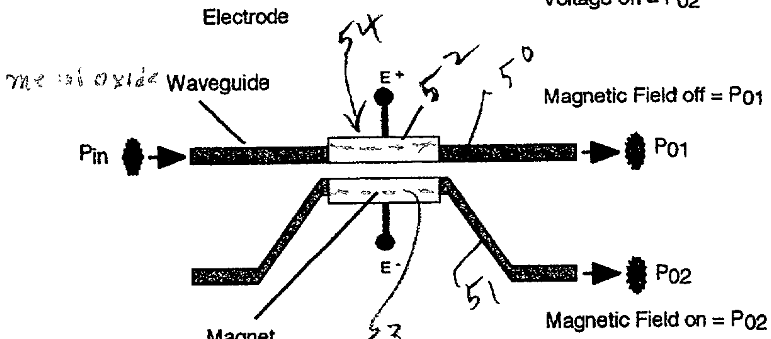


Fig 4
Magneto-Optic

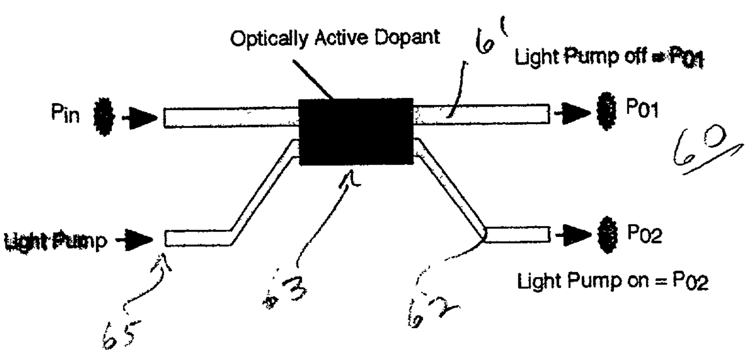
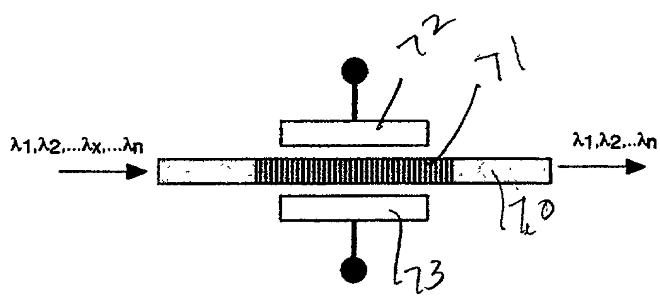


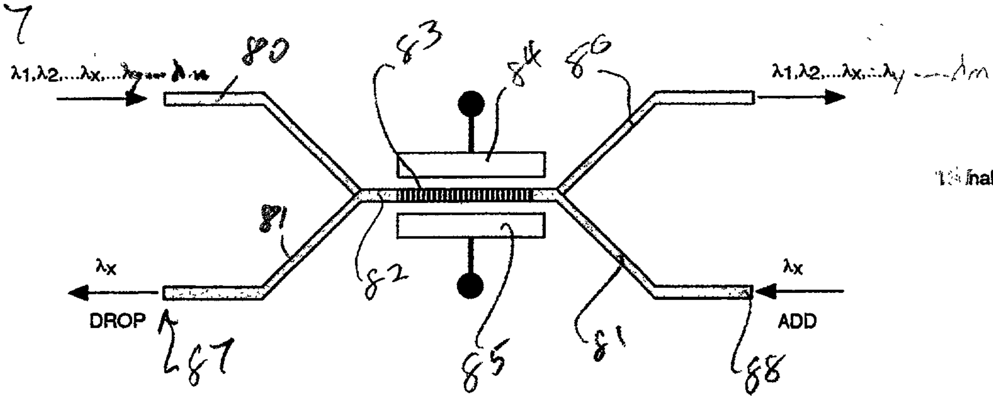
Fig 5
All-Optical

Fig 6



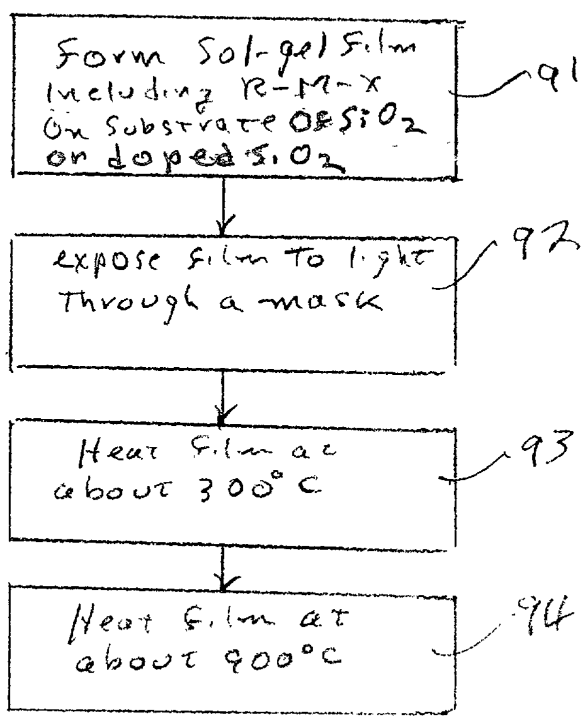
Tunable Bragg Grating Filter

Fig 7



Tunable Add/Drop Filter

Fig 8



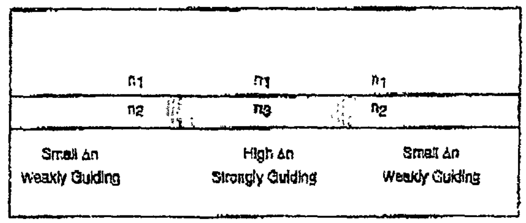


Fig 9
Waveguide structure with altered refractive index profile

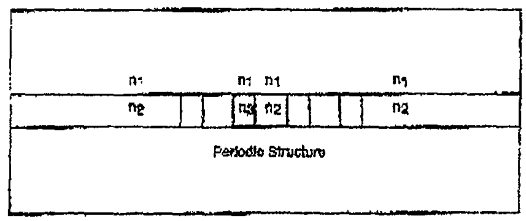


Fig 10
Waveguide structure with altered periodic refractive index profile

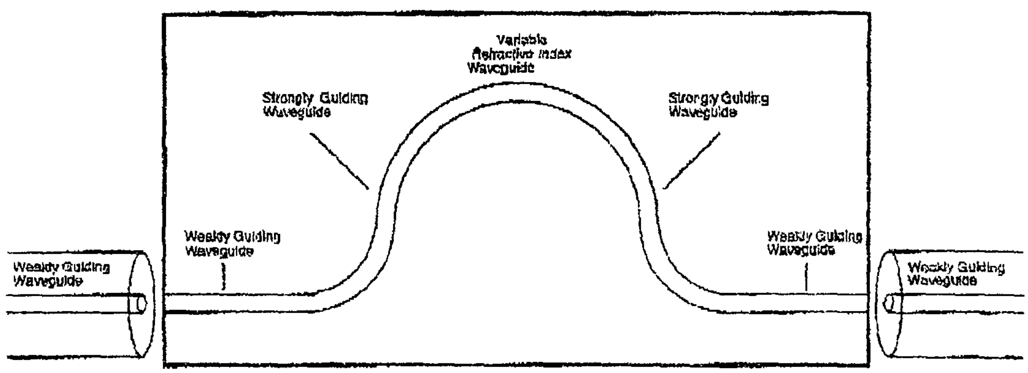


Fig 11
Waveguide structure with tight curvatures using variable refractive index profiles

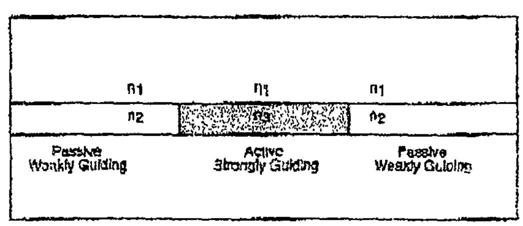
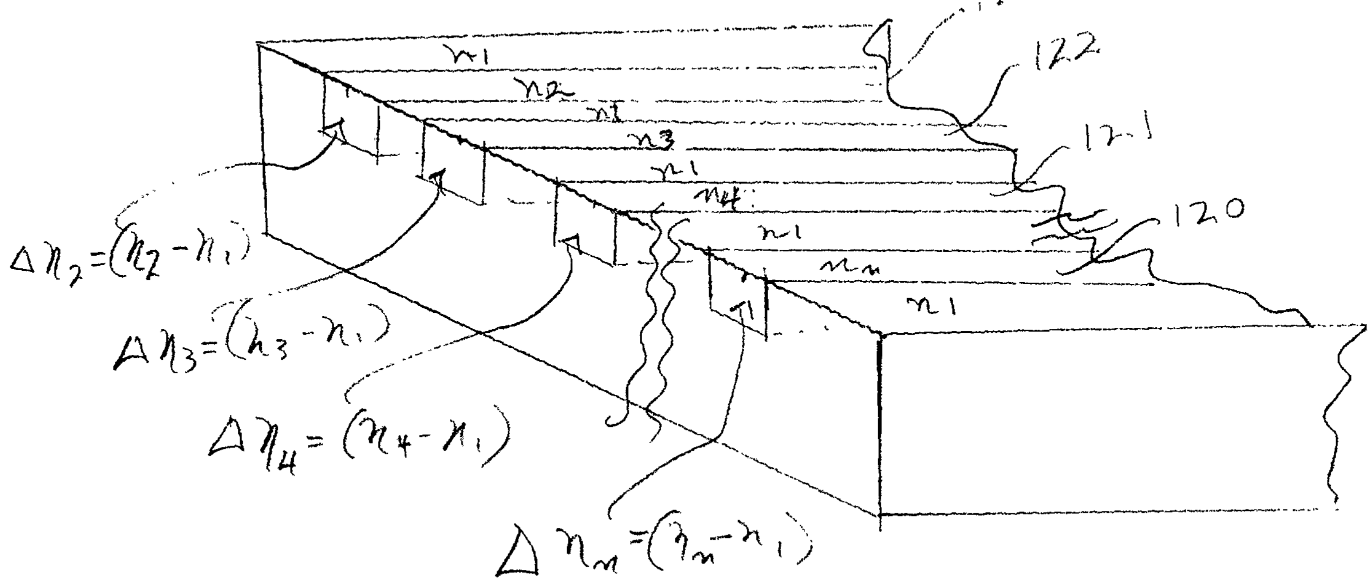


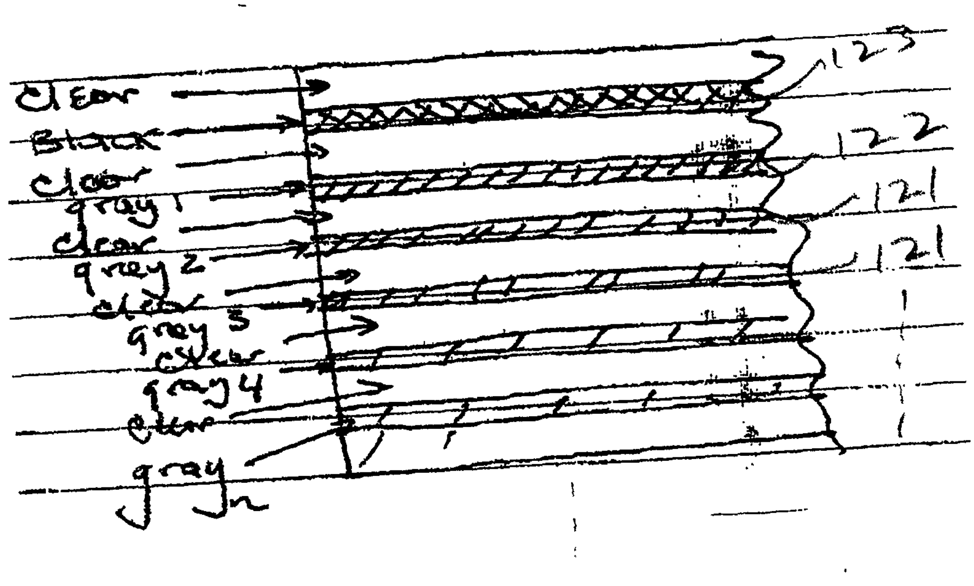
Fig 12
Active waveguide structure with variable refractive index profiles

Fig 13



n1
n2
n1
n3
n1
n4
n1
nn
n1
123
122
121
120
$\Delta n_2 = (n_2 - n_1)$
$\Delta n_3 = (n_3 - n_1)$
$\Delta n_4 = (n_4 - n_1)$
$\Delta n_n = (n_n - n_1)$

Fig 14



clear
Black
clear
gray 1
clear
grey 2
clear
grey 3
clear
gray 4
clear
gray n
123
122
121
121

Fig 16

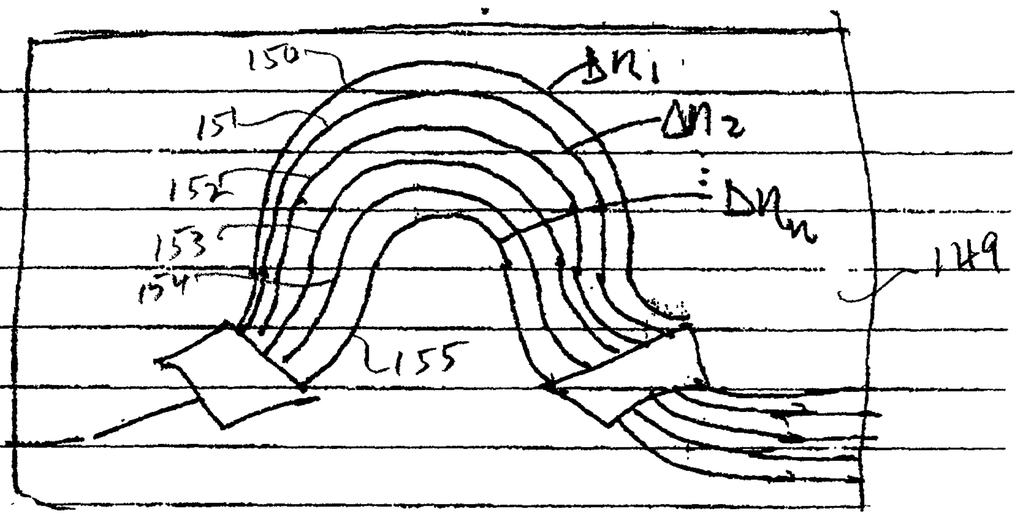

150
151
152
153
154
155
Δn_1
Δn_2
Δn_n
149

Fig 15

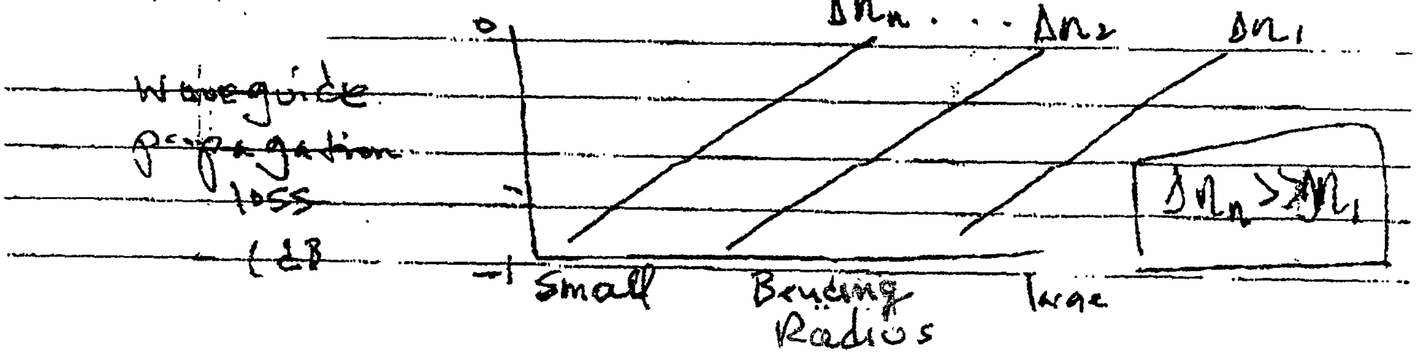
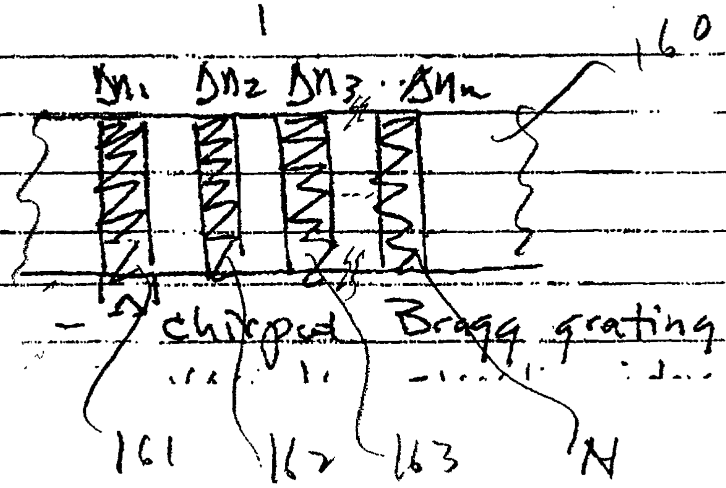

Waveguide propagation loss (dB)
0
-1
Δn_n . . . Δn_2
Δn_1
$\Delta n_n > \Delta n_1$
Small
Bending Radius
large

Fig 18



Prior Art

Fig 17

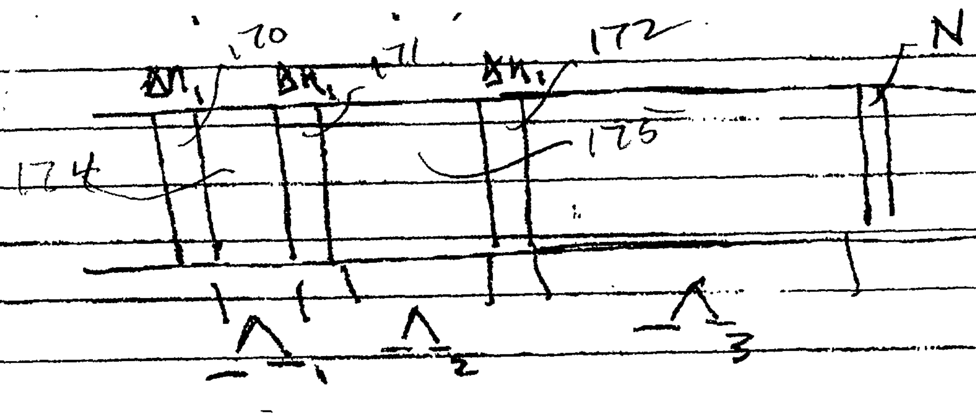


Fig 19

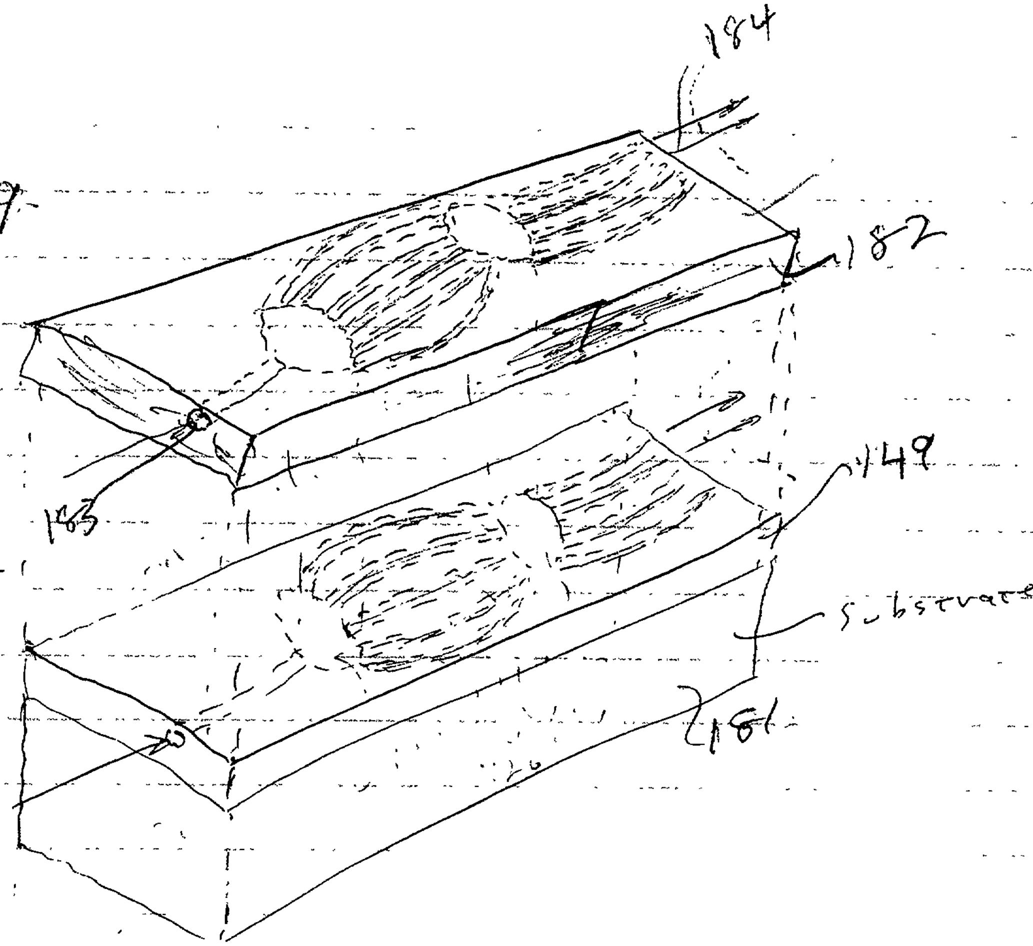
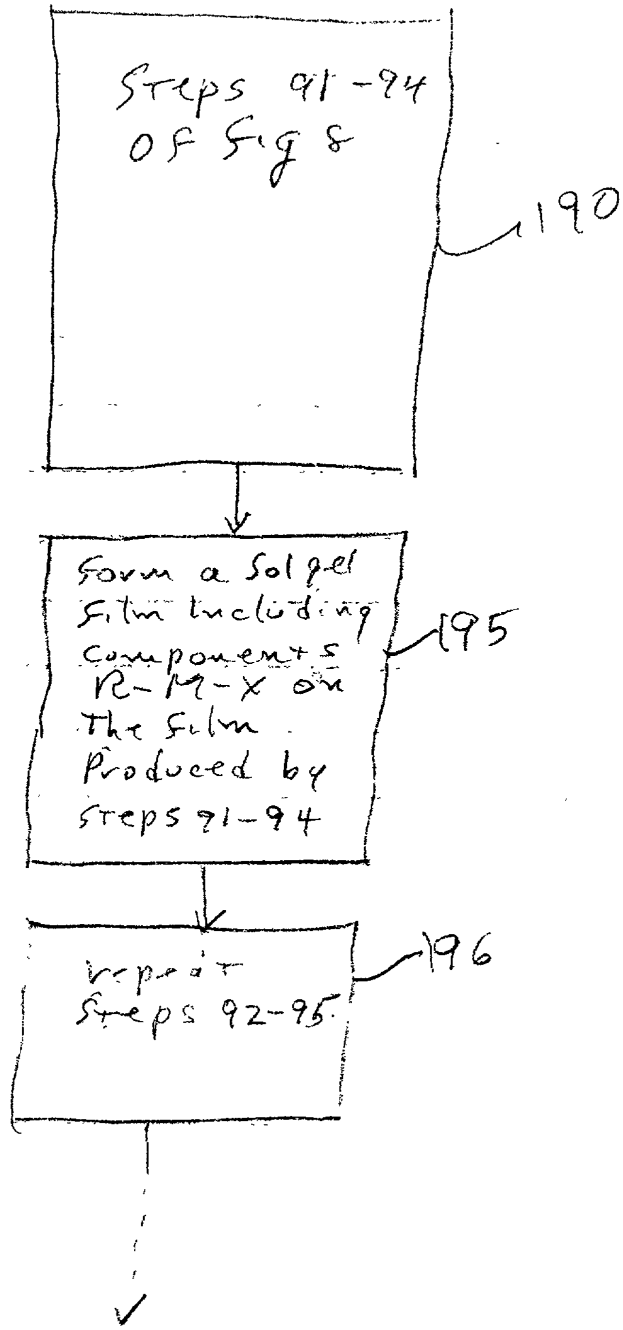


Fig 20


Steps 91-94
of Figs 8
190
Form a Solgel
film including
components
R-M-X on
The film
Produced by
steps 91-94
195
repeat
Steps 92-95
196

-118

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

ENGLISH LANGUAGE DECLARATION

As below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

Thermally-Assisted Photolithographic Process Using Sol-Gel Derived Glass And Products Made Thereby

The specification of which
[X] is attached hereto
[ ] was filed on ________________________ as
application serial no.________________________
and was amended on________________________
(if applicable)

I hereby state that I have reviewed and understand the contents of the above identified specification, including claims as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, Sec. L.56(a).

I hereby claim foreign priority benefits under Title 35, United States Code, Sec. 119 of any foreign application(s) for patent of inventors certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

Prior foreign application(s)			Priority claimed	
________ (number)	________ (country)	________________ (date/month/year/filed)	[ ] yes	[ ] no
________ (number)	________ (country)	________________ (date/month/year/filed)	[ ] yes	[ ] no
________ (number)	________ (country)	________________ (date/month/year/filed)	[ ] yes	[ ] no

I hereby claim the benefit under Title 35, United States Code, Sec. 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner

provided by the first paragraph of Title 35, United States Code, Sec. 112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, Sec. 1.56(a) which occurred between the filing date of the prior application and the national or PCT filing date of this application:

(Application Serial No.)	(Filing Date)	status (patented pending, abandoned)
(Application Serial No.)	(Filing Date)	status (patented pending, abandoned)

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Sec. 1001 of Title 18, United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith. (list name and registration number)

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